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Improving Tree-Thinking One Learnable Skill at a Time

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ORIGINAL SCIENTIFIC ARTICLE

Improving Tree-Thinking One Learnable Skill at a Time

Kristy Lynn Halverson

Abstract Representations are a critical way to communicate scientific knowledge. Systematists biologists are acknowledged as expert tree thinkers who can both read and build phylogenetic trees (e.g., cladograms) accurately. The purpose of this study was to identify the core skills essential to help college students overcome tree-thinking challenges. In this study, I used pre/posttests, interviews, weekly reflective journal entries, field notes from course observations, and student responses to coursework to learn how upper-level college biology students developed representational competence with phylogenetic trees. I identified essential core skills by investigating students' tree-thinking progression over the course of the semester. Three major patterns emerged from the data: (1) students became better tree readers than tree builders by the end of the plant systematics course; (2) core skills are essential for students to develop tree-thinking competence; and (3) tree reading skills developed before tree building skills. By diagnosing challenges students face with tree-thinking, identifying core skills necessary to overcome these challenges, and developing a starting point for a context-based framework for representational competence, this study adds to our understanding of critical elements necessary for designing effective instructional interventions and improving student learning with phylogenetic trees.

Keywords Tree-thinking · Cladogram · Phylogenetic tree · Challenges · Core skills · Representations · Evolution

People use representations to explain how we make sense of things on a daily basis. Often biologists generate phylogenetic representations to express their understandings of the evolutionary relationships they are investigating (Matuk 2007). In systematic biology, biological information is organized using phylogenetics and "evolutionary trees serve not only as tools for biological researchers across disciplines but also as the main framework within which evidence for evolution is evaluated" (Baum et al. 2005). Evolutionary biologists interpret phylogenetic trees in accordance with how they illustrate evolutionary histories or inferred evolutionary relationships among a set of taxa (Baum and Offner 2008). Scientists compare phylogenetic representations in search of similar patterns to provide support for hypothesized relationships among taxa. They find similarities by comparing monophyletic groups, or clades, across representations. Being able to correctly interpret and compare phylogenetic trees is a critical component to developing tree-thinking.

A second component of tree-thinking involves generating phylogenetic trees by isolating and interpreting informative data into evidence of evolutionary relationships. There are many different styles of representations an expert could generate if asked to draw a visual representation illustrating the relationships among taxa (e.g., Matuk 2007). In addition, scientifically accurate phylogenetic representations share the following features: relationships are grouped based on evolutionary histories and common ancestry, all organisms are related and are connected within a single representation, taxa are placed at the terminal tips assuming hypothetical ancestors at nodes, and consensus nodes are used when relationships are uncertain. People must share this common understanding of how to accurately interpret the representation in order to effectively communicate.

Theoretical Framework

Representations provide a different way of presenting information than verbal lectures and are critical for

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communicating abstract science concepts (Gilbert 2005; Mathewson 1999; Patrick et al. 2005). Comprehension of verbal descriptions is aided by both accompanying visualizations and when learners generate visualizations from a series of descriptive statements. These types of visualizations help develop a deeper understanding of the relationships among phenomena. The primary importance of using such visual tools to facilitate learning is that the visualization itself, animated or still, should explain, not merely show, content. For example, in science, graphic representations such as phylogenetic trees are used to display data, organize complex information, and promote a shared understanding of scientific phenomena (Kozma and Russell 2005; Roth et al. 1999). Students must learn how to use representations to construct meaning through interpretations of underlying ideas rather than rely primarily on the surface features of representation to derive meaning (Chi et al. 1981).

Kozma and Russell (2005), in the context of chemical representations, proposed a set of core skills that must be developed in order to develop competence in the use of visual representations. These skills include an individual being able to use, generate, describe, and compare appropriate representations when communicating with a particular discipline. Once these skills are developed, a learner should be able to effectively use a variety of representations, thereby achieving representational competence. When a learner achieves representational competence, he/she can begin shifting the external representation into an internal representation, or a mental image that can be manipulated (e.g., scanned and rotated) to improve performance on visual tasks, memory tasks, and cognitive problem solving (Botzer and Reiner 2005; Clement et al. 2005; Gilbert 2005). Although Kozma and Russell (2005) proposed the core skills for chemistry education, these skills have not been empirically tested in or beyond chemistry.

Literature Review

A major aspect of learning to read and to construct representations involves determining which features are and are not pertinent (Van Fraassen 2008). Unfortunately, phylogenetic trees are not well understood by students (Baum et al. 2005; Gregory 2008; Halverson 2010a; Meir et al. 2007; Omland et al. 2008; Sandvik 2008; Thanukos 2009). For example, students often misinterpret phylogenetic trees because they focus on superficial features. This focus leads many students to misinterpret phylogenetic trees by "reading across the tips" and assuming "more intervening nodes equals more distantly related," basing evolutionary relationships on the physical proximity of species to one another in the representation (see Baum et al. 2005; Gregory 2008; Meir et al. 2007; Perry et al. 2008). These errors prevent students from tracing implied taxa lineages that can be mapped from the tip to the root of the tree (Halverson 2009, 2010b). But not all superficial tree reading errors are based on proximity. Students do not always recognize that altering the orientation of a tree or format of the branches (e.g., straight, bent, or circular) does not alter the relationships represented (Catley et al. 2009; Halverson et al. 2011; Novick and Catley 2008). Furthermore, branches on a phylogenetic tree can swivel around nodes and still represent the same branching pattern, thus the same relationships among taxa.

Tree-thinking is not restricted to interpreting and building single representations. Scientists often compare trees by looking at informative branching patterns in search of evidence to support presented hypotheses (BioQUEST 2006). Students struggle with mentally rotating branches and comparing patterns of relationships among trees (Halverson 2010a, b). The notion of tree-thinking can be inconsistent with everyday thinking about biological groups and their relationships (Cobern et al. 1999). When considering tree-thinking initially, some students do not use tree representations presented to draw conclusions about evolutionary relationships depicted among taxa. Rather, these students base their interpretations on erroneous prior ideas about the organisms, such as habitat, morphology, behavior, etc. (Gregory 2008; Halverson et al. 2011). But while these characteristics may represent an accurate knowledge about the organisms, they are not appropriate for understanding evolutionary histories. This type of interpretation indicates that students tend to lump organisms based on single characteristics and/or inappropriate characteristics, rather than looking holistically at the taxa to understand the basis of how tree hypotheses are generated (Gendron 2000).

Generating phylogenetic trees is a cognitively complex task and without explicit scaffolding, many students are unable to transfer any empirical data into a visual structure (Gendron 2000; Halverson 2009). Still, difficulties with tree construction extend beyond technical aspects to the foundational basis of what trees represent. Evolutionary biologists recognize relationships among species by using foundational concepts such as inheritance, the four forces of evolution, and parsimony to develop hypotheses and build phylogenetic trees. By ignoring critical data and/or using uninformative evidence, students are unable to construct scientifically accurate phylogenetic trees (Halverson 2009; Halverson et al. 2011; Van Fraassen 2008). Student ideas about evolution can impact the way students visualize evolutionary relationships among organisms. For example, if students viewed evolution as progressive, they tended to interpret trees in a directional manner and generate ladderized or flow chart representations (Halverson et al. 2011; Halverson 2009). Without a solid understanding of how to interpret and build phylogenetic trees, students cannot advance their representational competence enough to use trees to reconstruct ancestral states (Perry et al. 2008) and other application tasks.

Research Questions

The purpose of this study was to identify the core skills essential to help college students overcome tree-thinking challenges. To address this purpose, I asked the following research questions: (1) What are the trends in how students interpret, compare, and build phylogenetic representations throughout an upper-level plant systematics course? and (2) What core skills are essential for students to build representational competence in tree-thinking? This study uses a qualitative approach to investigate how students gain representational competence with phylogenetic trees throughout a course on plant systematics. By better understanding the core skills needed for students to develop representational competence with phylogenetic trees, we will be able to design an informed curriculum that enhances meaningful learning in evolutionary biology.

Method

Participants included 27 full-time undergraduate students enrolled in the lecture section of an upper-level, plant systematics course at a Midwestern research-extensive university during the spring 2008 semester (Table 1). Among these volunteers, I selected 13 key informants. I categorized key informants as students who volunteered for the two-part interview series.

The plant systematics course was organized primarily around phylogenetic tree-thinking. The instructor stressed evolution content at the beginning of the course to make explicit connections between the course content and tree representations. Throughout the course, he presented multiple styles of phylogenetic representations, used activities targeting alternative ideas about phylogenetic trees, and provided scaffolds for tree-thinking development (BioQUEST 2006; Halverson 2008, 2010b). Students' understandings were assessed through regular homework assignments, in-class activities, group discussions, exams and quizzes throughout the semester. My role as a non-participant observer (Patton 2002) was made evident to the students throughout the project.

Data Sources

To elicit students' ideas about phylogenetic representations and challenges they face when developing tree-thinking, I collected data using multiple open-ended sources throughout the entire semester. Using multiple data sources increased the validity of my research by being able to triangulate my findings.

Table 1 Participant demographics

	Percentage (n=27)	Pseudonym
Gender		
Male	59	
Female	41	
Grade level		
Senior	59	
Junior	30	
Sophomore	11	
Major		
Biology	44	Brenda[a], Roger[a], Chad[a], Kathryn[a], Krystal, Maggie, Mitch, Aaron, Emily, Bob, Cameron, and Karen
Fisheries and wildlife	33	Darren[a], Jared[a], Sally[a], Chip[a], Miranda[a], Abe, Jamie, Tim, and Lauren
Secondary education—unified science/biology	11	Jeremy[a], Brandt[a], and Peter
Forestry	4	Aimee[a]
Chemistry	4	Kristen[a]
Interdisciplinary—science	4	Randy

[a] Key informants

Online Reflective Journals

I administered weekly online reflective prompts via Blackboard. These questions ranged from assessing content knowledge and tree-thinking abilities to eliciting reflections upon instructional strategies. Each week's questions were designed to have students reflect on discussions and experiences from the previous week. More specifically, these prompts were designed so that I could identify the core skills students needed to become effective tree thinkers; I also used the prompts to recognize shifts in students' phylogenetic understanding and how students' perceived instructional interventions supported their learning.

Pre/Posttest

During the first week of class, I administered a two-tiered pretest modified from Baum et al. (2005) prompting students to explain how they approached tree-thinking and assessing their understandings of evolution. I administered a slightly altered posttest during the last week of the course, to assess students' understandings at the close of the semester. The posttest was altered to include more technical terminology and an additional four questions to assess students' ideas about evolution. I used the pretest explanations to customize the interview protocols which allowed me to probe more deeply into individual student's ideas.

Interviews

Thirteen students consented to act as key informants and participate in an interview series consisting of two 1.5-hour semi-structured interviews (Patton 2002). Each key informant scheduled individual interviews during the second and fourth month of the semester. Each interview explored plant-based tree-thinking tasks. Interview 1 included a series of questions probing students' reasoning as expressed on the pretest in addition to assessing tree reading skills and how students compared multiple phylogenetic representations. Interview 2 focused on having students reflect upon the semester and included a series of three think aloud tasks: building a phylogenetic tree, interpreting a phylogenetic tree, and comparing phylogenetic trees. I videotaped and audio recorded each interview to capture a holistic account of their responses. I also interviewed the instructor prior to the course so I could compare his expert responses to the students' responses. During this interview, the instructor engaged in and responded to the same tasks and prompts as the students. I transcribed each interview verbatim and reviewed each transcript for accuracy.

Coursework

I collected student responses from homework and exam questions designed to elicit explanatory responses about phylogenetic thinking components. For example, participants completed an activity debating the evolutionary ancestry of hippos and whales (BioQUEST 2006). Students were presented the scenario presented in Fig. 1:

> Scientists have compiled multiple data sources and developed two arguing hypotheses about the evolutionary relationships among the whales and various ungulates. Examine the following two trees (Fig. 1). In your own words, what are the evolutionary relationships illustrated between Cetacea (Whales and Dolphins) and Artiodactyls (Even-Toed Ungulates)

This assignment had students review a consensus hypothesis and compare it to multiple trees generated from single data sources (e.g., α-hemoglobin, cytochrome *b*, and skeletal/dental) in search of nodal support. Students responded to questions such as, "Is it possible to have support for a more basal clade if a more recent clade is not supported? Explain how or why not?" Student responses to these questions provided insights into their thinking periodically throughout the entire semester.

Field Notes

I observed all lecture meetings for the plant systematics course (30 meeting dates of 90 minutes each). During the observations, I recorded field notes about instructional supports used to teach tree-thinking skills, student involvement in the class, comments and questions presented about phylogenetics, and student strategies for solving systematics problems during in-class activities. When students interacted in small group activities, I observed the two groups that included key informants. I used my field notes from these group observations to inform my observations of the entire class for that period.

Data Analysis

I utilized all transcripts, field notes, expanded observation notes, and documents in data analysis. Rather than approach the data with predetermined themes in mind, I used an inductive approach to assess the ways students interpreted,

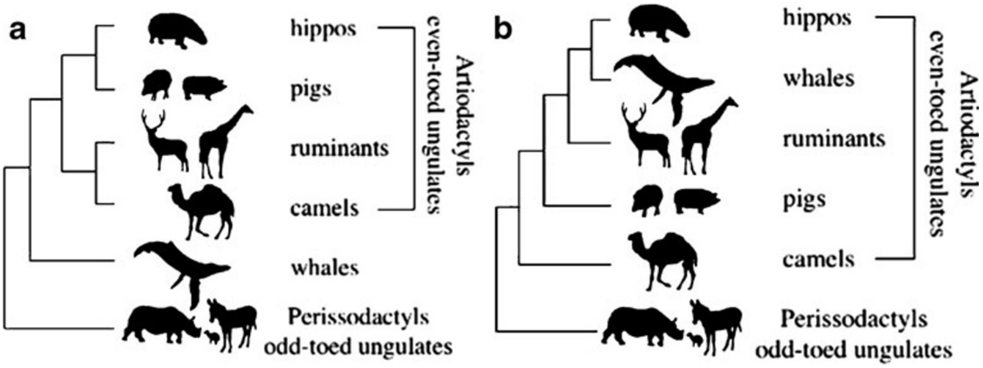

Fig. 1 Two trees illustrating opposing hypotheses about the evolutionary history of whales (Image taken from BioQUEST Curriculum Consortium (2006))

compared, and built phylogenetic representations. Some of the codes developed included: a main branch exists, when branches are flipped the tree meaning is altered, branch length illustrates time, relationships are related to tip proximity, and relationships are dependent on the number of nodal events. I grouped these initial codes into categories based upon similarities in responses. These categories allowed me to compare the reasoning processes and tree-thinking skills among data sources and among students. Then, I searched for patterns in the data to identify skills students developed and used throughout the course as well as skills used by the expert instructor. Once I identified patterns, I triangulated the findings using secondary data sources to ensure the conclusions accurately represented the data and were consistent with how students reflected upon their own learning.

Findings

Student performance in this study suggests that there are core skills necessary for developing representational competence in tree-thinking. Three major patterns emerged from the data: (1) students became better tree readers than tree builders by the end of the plant systematics course; (2) to be a highly competent tree thinker, students must develop core skills essential to both reading and building phylogenetic trees; and (3) tree reading skills developed before tree building skills.

Tree Reading Trends

Being able to interpret phylogenetic trees correctly is a critical component in developing tree-thinking that can be divided into different tasks such as tree interpretation and tree comparison. I identified ten different rationales students used to interpret phylogenetic trees and five different criteria students used to compare phylogenetic trees (Table 2). These approaches were not mutually exclusive—students used one or more interpretation approaches to make sense of phylogenetic representations.

Accurate Approaches

Students using scientifically accurate approaches to interpret phylogenetic trees based their reasoning on recent common ancestry or by looking at patterns of monophyletic groups among the taxa (that included a common ancestor and all of its descendents). Additionally, these students also accurately compared phylogenetic trees by identifying patterns of similarities and differences in monophyletic groupings across representations (clade comparison). They understood that monophyletic groups have to be the same in each tree for the trees to represent identical relationships.

Node-Focused Approaches

Several students focused on the nodes when interpreting phylogenetic trees. For example, some students considered the number and distance between nodes as highly informative factors to interpret relationships between species (nodal emphasis rationale). Other students viewed tree nodes more for their role in a mobile and based their rationales on swiveling branches around nodes (rotate branch rationale). For example, Abe supported his interpretations of relationships represented in phylogenetic trees because, “you can turn the tree at the node and thus switching the appearance, but not the relationships.”

However, these interpretations are lacking scientific content to justify the evolutionary meaning behind the relationships represented and sometimes led to confusion about how to accurately interpret changes to a tree. For example, Roger interpreted rotations to mean that phylogenetic trees could be manipulated to represent equal relationships among all of the taxa shown. Some of the students who used node-focused approaches compared trees based on perceived branch length. For example, rather than interpreting each branch as a lineage that extended from the root of the tree to the terminal tip, Darren interpreted lineages as extending from the terminal tip to the first node. Thus, when tree branches were swiveled upon a node, he viewed the new appearance as representing new relationships, because the branches now appeared to be different lengths than the original.

Branch-Focused Approaches

These students ignored the role of nodes and relied upon the physical branching patterns to interpret trees and often considered evolution to be progressive in nature. Scientifically, it is accepted that trees can be read in multiple directions, although time progresses from the root to the tips and species do not branch “off of” one another; rather, taxa diverge from a hypothetical common ancestor. However, students who focused on branches when interpreting trees either read through the representation in a single direction, e.g., top to bottom with relatedness having to come after the taxa in question (unidirectional reading rationale) or interpreted relationships in relation to a “main branch” that taxa “branch off from” (main branch rationale). For example, Miranda justified her interpretation of a simplified phylogenetic tree by stating, “All [the taxa] are coming off from the same main branch.” Most of these students used the physical branching pattern as their criterion compared phylogenetic representations for comparing trees, interpreting ladderized trees (only having primary branches) as representing different relationships than the same representations rotated so that they show hierarchical branching structures.

Table 2 Students' approaches used when tree reading

Rationale/criterion	Incoming ideas		Ideas at the end of the course	
	# Students	% Students	# Students	% Students
Tree interpretation rationales				
Common ancestry[a]	5	19	21	78
Monophyletic groupings[a]	0	–	8	30
Implied apomorphies	0	–	5	19
Rotate branches	0	–	8	30
Nodal emphasis	4	15	1	4
Main branch	11	41	2	7
Unidirectional reading	2	7	1	4
Proximity of tips	10	37	1	4
Physical measurements	2	7	0	–
Ecology of organisms	4	15	0	–
Tree comparison criteria				
Clade comparison[a]	5	19	21	78
Physical branching patterns	11	41	2	7
Branch length comparisons	3	11	1	4
Patterns in tip proximity	3	11	2	7
Style of representation	7	26	2	7

Note: totals are equal or more than 100% (27 students) because students could use more than one rationale/criterion when interpreting/comparing phylogenetic representations

[a] Indicates scientifically accurate understandings

Proximity-Focused Approaches

Students interpreted representations based upon proximity of the taxa represented either at the terminal tips (proximity of terminal tips rationale) or the amount of time/space between the tips and root (physical measurement rationale). Such that, taxa appearing closer together are considered more closely related than taxa that are further apart. For example, Bob measured the distance from the root of the tree to the most recent point of divergence as a way of interpreting relationships among organisms (Fig. 2). He stated, "The length of time between seals and horses having a common ancestor and diverging into two species is much shorter than that for the seal and whale." An emergent trend indicated that students who interpreted individual phylogenetic trees based on the proximity of terminal tips tended to compare relationships across trees based on patterns in tip proximity (patterns in tip proximity criterion).

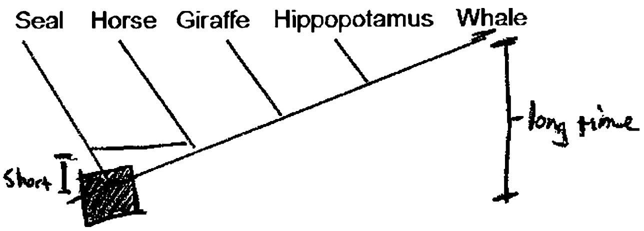

Fig. 2 Is the seal more closely related to the horse, the whale, or equally related to both? The scientifically accurate interpretation is the seal is equally related to the horse and whale

Organism-Focused Approaches

Although no character states were represented on the trees used for the tree interpretation questions in this study, some students still based their interpretation rationale on implied differences in character states among organisms (implied apomorphies rationale). Other students interpreted relationships using their prior knowledge of ecological characteristics of the organisms illustrated in the tree. For example, Aaron based his interpretation of relationships on the idea that "both are reptiles" referring to the lizard and crocodile presented in one tree rather than the common ancestry indicated between the crocodile and bird. In these cases, students ignored any potential patterns in branching structures of the tree.

Comparing Different Styles of Trees

Regardless of type of approaches students used to interpret trees, the style of the tree (e.g., diagonal, rectangular, or circular) influenced how some students interpreted and compared patterns of relationships among taxa. The circular representations were consistently most problematic for these students.

Tree Reading Core Skills

Emergent trends from the data revealed shifts in the rationales students used when interpreting and comparing phylogenetic trees over the course of the semester. For example, students who interpreted phylogenetic trees based on the proximity of organisms along the terminal tips or on knowledge about ecology tended to shift their rationale to rotation-based interpretations by the end of the course. This trend illustrates a shift from students using superficial location of taxa along the tips of the representation or ignoring the representation when forming conclusions about relationships among the taxa, to acknowledging scientific meaning in the representation and recognizing the mobile nature of trees. Another trend showed that students who began the course using a nodal emphasis rationale when interpreting trees shifted their rationale to focus on implied apomorphies and common ancestry by the end of the course. While these students still used the nodes to interpret relationships illustrated on the tree, they learned to recognize the symbolism of these intersections to represent common ancestry and divergence events. By the end of the semester, the majority of students (67%) consistently used scientific approaches to read trees (Table 2). These students recognized the scientific meaning of common ancestry and monophyletic groupings. Students also improved tree comparison skills. By the end of the semester, over two thirds (70%) of students used the clade comparison criterion when comparing phylogenetic representations. Major categories of skills that facilitated student improvements in tree reading included:

- Recognition and understanding: recognizing and understanding the meaning of key features/parts of a simple phylogenetic tree (e.g., branches, nodes, and time);
- Identification and use: identifying and using scientific approaches toward interpreting and comparing patterns of evolutionary relationships represented (e.g., monophyletic and paraphyletic groups) regardless of the style of representation; and
- Evidentiary support: using phylogenetic trees as evidence to support claims, draw inferences, and make predictions about phylogenies.

Recognition and Understanding At the beginning of the course, students did not know the parts or meanings of informative features on a phylogenetic representation. They learned phylogenetic terminology during the first month of the plant systematics course. At the beginning some of these students ignored the represented relationships and provided responses to tree reading questions based on their knowledge of each organism's ecology presented on the tree. For example, Aaron selected two organisms as most closely related because they "both are reptiles," although this was not consistent with the relationships represented by the phylogenetic tree.

Identification and Use Nearly half of the students (44%) identified key features of phylogenetic trees but were unfamiliar with the symbolic meaning each feature and pattern represented. For example, Miranda was able to define key features of a phylogenetic representation. But she was not able to apply her understandings of these features when interpreting a phylogenetic tree. She stated, "In tree 1, A and B are closer related to F. In tree 2, A and B are further related to F," (see Fig. 3). In a scientific interpretation of the two trees, species A and B are equally related to species F.

After one month into the course, 41% students could explain the scientific basis behind clades, common ancestry, branch rotations, etc. but were unable to use these ideas when interpreting a tree. For example, at this point in the semester, Kristen interpreted trees using a main branch approach, relying upon how she perceived organisms as branching off from one another rather than how they fit within a monophyletic group and she was unable to build a tree. Prior to tree-thinking instruction, Brandt's responses to tree reading questions suggested that he counted the number of nodes to determine relationships between the terminal tips of a tree regardless of presence or absence of taxa. For example, he interpreted that a seal was more closely related to a horse than to a whale because "the divergence on the lineage that led to the horse is only one up from the seal" (see Fig. 4).

Jeremy relied on common ancestry to read a tree. He could verbally describe relationships on a given tree in addition to recognizing and defining informative features of the tree. When he compared patterns across phylogenetic representations he focused on differences in patterns of branching or the style of representation. If the tree appeared to have more bends in the branches he considered that to represent different patterns of relationships regardless of what was actually represented among the taxa. He was not able to make comparisons of patterns across trees or transfer their understandings to different styles of representations.

Evidentiary Support Chip used scientific reasoning to read and compare phylogenetic trees accurately over the course of the entire semester. For example, he interpreted relationships based on common ancestry and compared phylogenetic representations accurately based on clade patterns regardless of the representation style. Chip was also able to select appropriate representations to support a given phylogenetic scenario and use trees to make predictions and support claims. For example, during the interview, Chip selected a phylogenetic tree as being most appropriate to show relationships among species over examples of historic representations and flow charts. He stated the tree was "easy to read" and was good "to show relatedness between different taxa." He was critical of the other models and thought they "would be very difficult to show time"

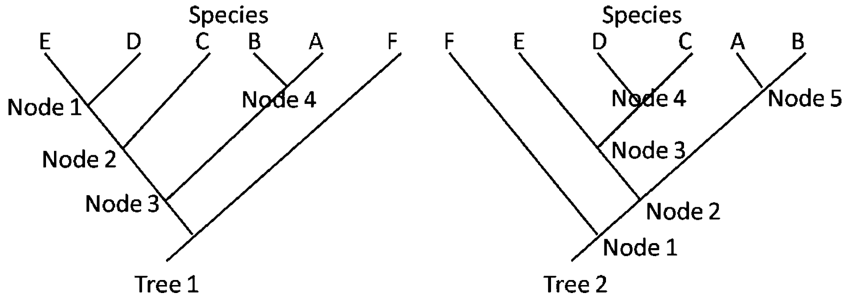

Fig. 3 Explain how these two attached trees are the same or different

and the flow chart was problematic because it showed taxa evolving into other taxa. Chip also used phylogenetic trees to make predictions about ancestral states and how new species could be integrated into an existing phylogeny.

Tree Building Trends

A second critical component in developing tree-thinking involves the ability to build accurate phylogenetic trees. The instructor gave students tree building tasks during the semester expecting students to generate visual representations illustrating how given taxa were related to one another. I found that students either did not complete the tasks (no representation) or generated one of nine types of representations (Table 3). Although some images shared characteristics with multiple types of student-generated representations, I classified each image by the primary type of representation generated. Student generated representations were often consistent with the approaches and criteria used for tree reading.

Categories of Student Generated Representations

Accurate Tree Representations Phylogenetic diagrams were the most scientifically accurate representations generated by students. Each of these diagrams represented key features expected in a phylogenetic tree and correct or nearly correct relationships among the organisms.

Alternative Tree Representations Students segregated taxa into multiple trees when illustrating a single phylogenetic scenario implying that different groups of organisms (e.g., plants and animals) are not evolutionarily related to one another. Other students created ladderized trees implying that evolution was progressive. Students who used branch-focused approaches often drew trees with taxa along branches, emphasizing the inaccurate notion of a main branch and organisms evolving off of other branches.

Alternative Tree-Like Representations Many students created tree-like representations that included taxa at the "nodes." These representations included flow charts illustrating species evolving into the other species, dichotomous keys illustrating taxonomic relationships among taxa, and ecological webs illustrating relationships among taxa based on trophic levels.

Alternative Non-tree-Like Representations Not all students attempted to create trees to represent relationships among taxa. For example, Aaron took a literal interpretation of the

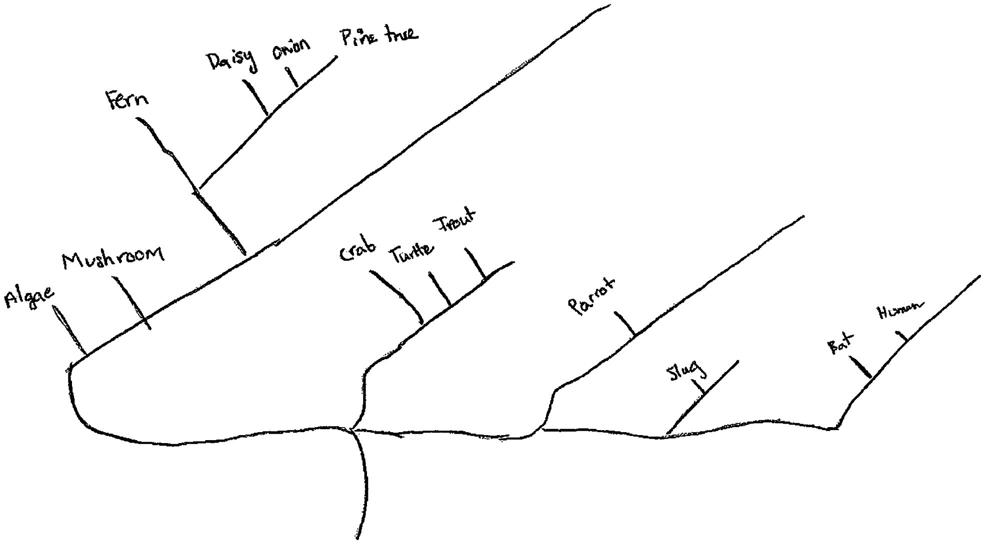

Fig. 4 Brandt's representation at the beginning of the course

Table 3 Types of student generated representation

Type of representation	Beginning of the course		Completion of the course	
	# Students	% Students	# Students	% Students
Phylogenetic diagram	2	7	10	37
Segregated organisms	4	15	3	11
Single progressive tree	6	22	6	22
Taxa along branches	2	7	–	–
Flow chart	3	11	–	–
Dichotomous key	5	22	5	19
Ecological web	1	4	–	–
Picture of the organisms	1	4	–	–
Written lists	1	4	2	4
No representation	2	7	1	4

task and drew pictures of all the organisms in the environment they would be found. Other students opted to compose written lists grouping how taxa might be related (e.g., lists of plants, fungi, and animals).

Tree Building Core Skills

Overall, tree building improved over the course of the semester, but specifically, three trends emerged from the data related to shifts in the types of student generated representations: (1) 15% of students generated less accurate representations; (2) 30% of students generated similar styles of representations; and (3) 55% of students generated more appropriate representations (37% of all the students generated scientific representations). The types of representations students generated were consistent with the approaches they used to interpret and compare phylogenetic trees. For example, students who generated a single progressive tree, interpreted relationships represented in phylogenetic trees using a main branch approach. By probing the steps students took to generate representations and their interpretations of their representations throughout the course, and by observing students tree building activities, I identified core skills essential for students to develop as they became tree builders. These skills build upon the foundational tree reading skills. Once a student can interpret a phylogenetic tree accurately, the major categories of skills that facilitated student improvement in tree building included:

- Distinguishing evidence: distinguishing between informative and erroneous evidence as it related to evolutionary relationships.
- Using evidence: using this evidence when constructing a hierarchical branching representation that symbolizes the likely evolutionary relationships among given taxa;
- Communication: being able to verbally describe, discuss, and manipulate their representation.

Distinguishing Evidence After multiple tree building opportunities, Brandt showed initial evidence of purposeful selection to isolate appropriate phylogenetic data. “I don’t like the characteristics on this data matrix. I’m not sure if things like location or being edible make for good data when constructing phylogeny. I don’t think me being able to eat tells me much of its evolution, but maybe I’m wrong.” His data selection process was refined after completing the Pseudocot fossil activity.

By the end of the course, Brandt consistently used only informative data to help understand evolutionary relationships among organisms. When asked how he would help someone else understand tree building, he offered a vague response that did not explain how one could transition from data to a data matrix to a phylogenetic tree representation. This led me to believe he did not fully understand the processes involved with tree building.

Using Evidence At the beginning of the course, Brandt constructed a phylogenetic tree depicting the relationships among multiple flora and fauna, he generated a single representation that was comb-like and divided organism by taxonomic type (see Fig. 4). Furthermore, the empty terminal tips suggested the presence of main branches. He provided no rationale for his representation. Additionally, there were three organisms left off of the diagram completely: dolphin, oak tree, and fly. At this point in the semester, Brandt had also not developed all of the identified tree reading skills. During my initial interview with Brandt, he admitted that the tree building questions were difficult for him at the beginning of the course because he had “no idea how to go about doing that.” He reviewed his initial tree from the pretest and told me that he should have based the relationships on apomorphies and modified the branches so that all of the organisms were derived from a single lineage. When I asked him to construct a new tree, Brandt initially drew a single line along a blank page to begin his phylogenetic tree. This action suggests the idea of a “main branch.” When probed why he took this action, Brandt responded, “It’s like a reference. I can’t remember the term, maybe it’s an out group.” He went on to add branches based on how he thought the taxa might be related and commented that, “this looks like a ladder, I don’t like it.” So while he recognized that his representation was comb-like in nature, he did not take measures to correct this issue.

Communication At the end of the second interview, we discussed the differences between tree reading and tree building. Brandt offered his insights:

> I think tree building requires you to have a better understanding of it. Reading, it is just given to you, but with building it takes a bit more knowledge of it. [the skills used for reading and building] should be [the same] but at the same time you have to take all of this data and make sense of it and sort it and then throw it onto a piece of paper but when you read a tree all you have to do is look at what is already organized. For students to understand it more I think you should have them draw trees even though it is tougher.

As Brandt described, tree building is cognitively a more difficult task that requires a core skill set that builds upon tree reading skills.

Roger was unable to generate any type of visual representation at any point during the course. And, at the beginning of the course, Aaron drew a literal image of the given organisms and described the ecological relationships they shared. Neither student had past experience with phylogenetic trees. Over the course of the semester, students enrolled in the plant systematics course were guided through numerous tree building activities, during and outside of class time. But, by the end of the semester, Roger was still unable to generate a visual representation. At this point, he misinterpreted patterns of relationships represented on phylogenetic trees and did not understand how to transform raw data into a visual representation symbolizing how taxa shared evolutionary histories. These students had not developed core tree reading skills and were unaware of how to infer phylogenies from a given set of taxa.

Bob generated a representation at the beginning of the course that was consistent with building a phylogenetic tree. He also had previous experience with reading trees. By the end of the course, Aimee and Chip had developed each of the core tree reading and building skill sets. Aimee used her understanding of phylogenetics to generate a rectangular phylogenetic tree that represented accurate relationships among the plant taxa (see Fig. 5). Furthermore, both students were able to describe their trees and redraw them in various styles and orientations while maintaining the integrity and hierarchy of the relationships represented. For example, during Chip’s second interview, he developed a diagonal tree of 15 extant Pseudocot species, three extinct species, and an out group. He was later able to alter his diagram accurately to accommodate a new species and redrew the phylogeny as a rectangular diagram with several of the branches rotated around the nodes. Additionally, he was able to describe his scientific thought process while he was developing the representation and making alterations to accommodate the evidence provided.

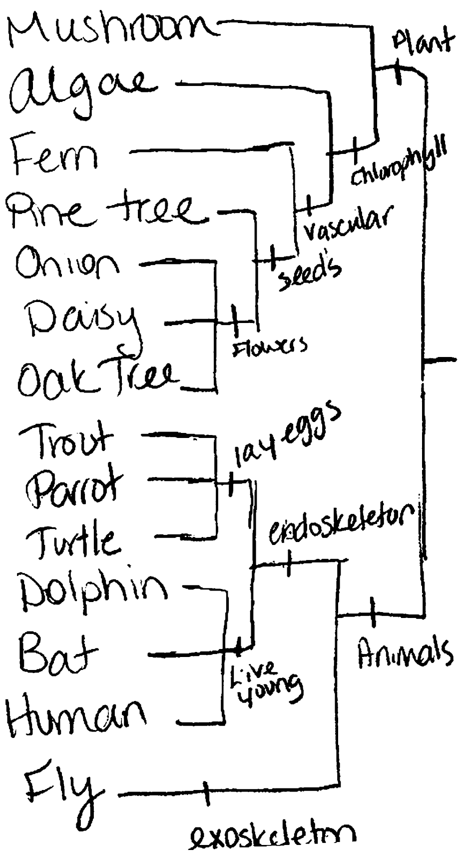

Fig. 5 Aimee generated a phylogenetic diagram using apomorphies to define monophyletic groups of taxa

Summary

Systematists are acknowledged as expert tree thinkers who can both read and build phylogenetic trees accurately. But tree reading and tree building represent tasks of varying levels of difficulty; tree building is more conceptually difficult and builds upon tree reading skills. Students must first be able to identify, understand and apply meanings to interpret trees. Only once this foundation is in place can students develop more advanced skills such as using a phylogenetic tree to support claims and draw predictions as well as generating trees. Students who generated advanced phylogenetic representations consistently interpreted and compared trees accurately. However, students who were poor tree readers and had not developed tree reading skills could not build phylogenetic representations accurately.

Discussion and Implications

Representations can enhance learning from texts, improve problem solving, and facilitate connections between new knowledge and prior knowledge (Cook 2006). By better understanding how students make sense of biological representations, particularly phylogenetic trees, I have identified two unique categories of skills, one for tree-thinking related to tree reading and the other for tree building development. While the seven core skills outlined by Kozma and Russell (2005) were related to tree reading, these skills were not all inclusive. Additionally, unique to evolution education, I identified a secondary skill set necessary to generate phylogenetic trees, a more cognitively difficult tree-thinking task.

All of these skills influenced the rationales and criteria students used to make sense of phylogenetic representations as well as the styles of representations they generated. As previously found (Baum et al. 2005; Gregory 2008; Halverson et al. 2011) several of the students in this study relied upon uninformative superficial structures of phylogenetic trees, such as bends in branches and proximity of tips, when making sense of the representation. Some students also relied upon their prior knowledge about ecology which interfered with accurate tree-thinking.

In systematic biology, phylogenetic trees act as a communication tool to map and evaluate evolutionary relationships among species (Cooper 2002). With the growing inclusion of phylogenetic trees in biology instruction, it is imperative that curriculum design reflects student needs for learning how to interpret and use these representations as well as help them overcome known tree-thinking challenges. The biology curriculum must be redesigned to recognize and target content misconceptions in addition to representation-based challenges that students face when learning tree-thinking. Some instructional resources (e.g., Gendron 2000; Meir et al. 2005; Perry et al. 2008; University of California Museum of Paleontology 2009) have attempted to address some of the listed tree-thinking challenges by explaining how scientists interpret and use data as evidence to build phylogenetic trees. During this plant systematics course, students were exposed to three instructional interventions challenging identified student tree-thinking difficulties (a 3D pipe cleaner activity (Halverson 2010b), a hypothetical plant activity (Halverson 2008), and an exercise comparing phylogenetic data (BioQUEST 2006)). These interventions were intended to explicitly target identified common tree-thinking challenges and provide a context for phylogenetic representations, help students identify and define the key features of phylogenetic trees, explain the symbolism of each feature, facilitate students' visualization of how branches can rotate around nodes and lineage mapping, allow practice with transferring evidence of phylogenies into a phylogenetic tree, and offer a chance to compare patterns of relationships across representations.

Current tree-thinking research takes a holistic approach and investigates tree-thinking as a culmination of tree reading and tree building. However, it has suggested that students' representational competence can change with the difficulty of the task (Barnea and Yehudit 2000; Kozma and Russell 2005). I presented evidence of students holding differing levels of competence when facing different tasks (e.g., tree reading versus tree building) even at the same point in a semester. Moreover, tree reading can be further expanded into different aspects such as interpretation and comparison. These views of tree-thinking allowed me to diagnose student problems within specific areas of tree-thinking and identify essential skills.

Representations are critical for communicating abstract science concepts (Gilbert 2005). Ignoring how students use and develop representations will prevent them from developing expertise in their field. Rather, we need to focus on helping students learn how to interact and communicate using scientific representations accurately. By diagnosing challenges students face with tree-thinking, identifying core skills necessary to overcome these challenges, and developing a starting point for a context-based framework for representational competence, this study adds to our understanding of critical elements necessary for designing effective instructional interventions and improving student learning with phylogenetic trees. Research-based instructional interventions facilitate improvements in representational competence with phylogenetic trees, maximizing the potential of evolution education and improving science literacy.

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